Coordinated Control of Ocean Going Vehicles

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***Abstract*— The experimental setup and data from the final demonstration of the FP7 Coordination for Control (C4C) project are presented and discussed in the framework of the control architecture and software implementation developed by the LSTS laboratory from Porto University. The demonstration took place in the Leixões harbor in June 2011 and involved autonomous underwater vehicles, autonomous surface vehicles, our gateways (centralized communications hub for maritime assets, supporting several types of wireless and underwater networks) and a Long Baseline system. Demonstration scenarios are presented together with the technologies developed along the project and the results obtained.**

I. Introduction

The Underwater Systems and Technology Laboratory (LSTS) aims the creation of networked vehicles systems constituted by human operators, heterogeneous autonomous vehicles and other sensing devices. LSTS has already built autonomous vehicles of different types, namely Autonomous Underwater Vehicles [1], Autonomous Surface Vehicles [2], Unmanned Air Vehicles [3], Remotely Operated Vehicles [4] and communication Gateways, Manta [5] (see figure 1). We provide an overview of the developments for the C4C project and describe how these developments were integrated and demonstrated at sea. The developments were targeted at solving the coordination and control problems of multiple autonomous underwater and surface vehicles. Developments include the advanced controls coordination control, dynamic programming based control, supervisory control and plan coordination and associated systems and technologies. This is done in the framework of the LSTS reference control architecture and supported by the LSTS software tool chain, unmanned vehicles (AUVs, ASVs, and UAVs) and communication and sensing devices.

We start by briefly describing each of the proposed scenarios for the demonstration. Afterwards we present the approach adopted to solve each of the problems. We then show some of the results obtained in the demo runs and finish by listing a few conclusions and ideas for future work along the same line of work.

II. Demonstration Scenarios

We considered 5 distinct scenarios to demonstrate the capabilities of the technologies developed in the laboratory:

1) **Mapping with mixed initiative interactions** - Concerns single-vehicle operations. An AUV is tasked to find the maximum depth in a given area in a mixed initiative fashion – the human operator is in the planning and control loop.
2) **High level supervision** - In this concept of operation an AUV loads several mission plans into the on-board computer before diving and is then able to switch among them.
3) **Follow vehicle over acoustic modem** - The NAUV was required to track the (x,y) position of *Swordfish* at a given depth.
4) **Formation control over acoustic modem** - NAUV and Swordfish performed formation control by travelling along two known parallel paths.
5) **Dynamic programming based feedback control** - This is a feedback controller which uses a value function encoded in a look-up table to derive optimal feedback controllers.

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Fig. 1. From top left to bottom right: Swordfish ASV, Adamastor ROV, Light AUVs (LAUV), Antex UAV, nAUV and Manta Gateways.

III. Technologies Developed for the Demo

Coordination and control technologies were implemented on the framework of the LSTS control architecture with the help of the LSTS Neptus-IMC-DUNE software toolchain (DUNE is the on-board software; Neptus is the off-board control and command framework and IMC defines a common format for data transfer among all LSTS software modules in a communications network [6]). This entailed the implementation of:

A. Mapping with mixed initiative interactions

The operator commands the AUV to execute an initial mission plan targeted at surveying the area to collect some preliminary bathymetry data. The AUV dives, executes the mission plan and surfaces. The operator extracts bathymetry data from the AUV using high speed communications (WiFi) and plots the bathymetry map in Neptus. Based on this preliminary map, the operator then designs a new mission plan for the vehicle to refine the bathymetry map of a selected area. A plan to cover a certain area may also be generated by Neptus itself. The vehicle was equipped with an Echo Sounder pointing downwards used to acquire altitude measurements of the water columns. Adding these values with the depth measurements acquired by the pressure sensor, the depth of the water column was computed.

B. High level supervision

Coordinated plans were created where the mission supervisors allow vehicles to execute mission plans encoded as a graph of maneuvers where the switching conditions can either be triggered by vehicle events or by external messages. Moreover, the vehicle supervisor will accept external commands to switch among a list of pre-loaded mission plans stored in a database. Those commands were received via acoustic communications if the vehicle was underwater. Nonetheless, multi-mode communications were integrated so the mission supervisors would automatically select the fastest and more reliable communication channel in case more than one is available.

C. Follow vehicle over acoustic modem

A new maneuver was developed to follow a vehicle broadcasting its position through acoustic modem or WiFi. Participating vehicles were equipped with Benthos acoustic modems for this purpose. In this case, Swordfish and NAUV were used. The mission specifications for both vehicles are presented next. Each vehicle was commanded to execute a given specific maneuver. The Swordfish had to describe a path in the form of a rectangle. NAUV had to follow it underwater. This was made possible by having the Swordfish broadcasting its position via the modem. NAUV tracks the broadcasted position by keeping a distance offset configurable by the user. A built-in protection would command the NAUV to stop, to prevent collisions, if the distance to Swordfish dropped below a safety threshold. From a control point of view, NAUV tracks way-points, yet these are fired according to Swordfish's last received position. NAUV will abort in case the time elapsed since the last communication exceeds a given time-out. The follow vehicle maneuver can be used on any sort of vehicle or system, as long as there is a vehicle broadcasting its location (acoustically or via WiFi) using the IMC protocol. The maneuver will switch to WiFi communications for exchanging position data if WiFi communications become available to the two vehicles. However, as long as the NAUV is submerged, the WiFi link will not be present.

D. Formation control over acoustic modem

Two maneuvers were developed for this scenario. One is based on a Sliding Mode Control (SMC) law and the other one uses Model Predictive Control (MPC) to achieve optimal control of the formation of vehicles. Acoustic communications were performed with three Benthos modems. We used Time Division Multiple Access (TDMA) to prevent acoustic transmission collisions. We used three slots instead of two (one for each vehicle and one for the Benthos modem connected to the onshore control center) for the operator to supervise the demonstration, and abort it, in case there was a need to. We choose to use Swordfish instead of another AUV to enable visual tracking of the experiment by the observers. We also kept the NAUV at the surface for the same reason. This is the most adverse environment for underwater communications and for NAUV control authority (there are turbulent flows around the propeller and the fins and the propeller is not submerged at all times).

E. Dynamic programming based feedback control

The controller was implemented in the on-board software, DUNE. We used numerical methods for solving the Hamilton-Jacobi-Bellman equation for dimensions higher then two: this is targeted at calculating the value function for optimal control problems with simple, but representative, vehicle dynamics. This is done off-board and loaded into the memory of the vehicle executing the *DPbasedcontrol* maneuver. We considered single vehicle operations on the horizontal plane and the problem of following a path within a given maximum cross-track error. This will translate to a set of state constraints. The idea is to enable a more relaxed control for systems subject to persistent measurement errors and (bounded) disturbances: the control effort will be stronger when the system is near the boundary of the tube and more relaxed when it is near the reference path. Moreover, our approach may also handle model uncertainty. The state constraints are employed to ensure strong robustness properties. This is done in the framework of invariance analysis: given a bounded disturbance, find the set of initial states from which the system is able to respect the state constraints afterwards (maximal controlled invariant set) (see, e.g., [7]). The results presented in this document were submitted for publication as [8].

IV. Results

Once again the results presented are oriented by each of the scenarios performed.

A. Mapping with mixed initiative interactions

As described in the technologies section, after the first bathymetry survey, the operator defined an area as a polygon and Neptus generated a plan for a more detailed bathymetry survey. The data collected by the vehicle's Echo Sounder was combined with the depth measurements and vehicle's position along the plan, in order to generate the map in figure 2. The colder the color, the deeper is the water column.

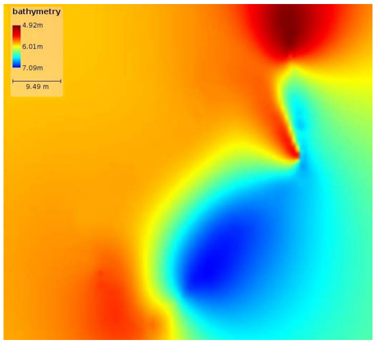

Fig. 2. Bathymetry map visualization using Neptus.

B. High level supervision

Both the NAUV and the onshore control center (where the human operators were located) were equipped with Benthos acoustic modems to allow for the plan switching commands to be sent. They were setup at a transmission rate of 600bps and in broadcast mode, i.e., any message from any of the peers could be received by all the others. Since the Benthos modems do not provide any built-in form of MAC to avoid acoustic transmission collisions (and resulting data corruption), we employed a simple and software-enabled Time-Division Multiple Access (TDMA) scheme. This scheme was characterized by a period Δ and n sequential slots of duration $\frac{\Delta}{n}$, that partition each TDMA period. In the demo we used a period of $\Delta = 18$ and $n = 3$ slots, one per vehicle (NAUV and Swordfish) and another one for the onshore modem. Naturally the Swordfish partition was not being used for this particular scenario, since this one concerns single vehicle operations only. Every period of $\Delta = 18$ seconds was thus partitioned in TDMA slots $[0, 6], [6, 12], [12, 18]$. All acoustic peers had their clocks synchronized at the start of the demo using NTP [9]. All data transmissions were encoded in the IMC data format, and we employed data compression to decrease the time required for a transmission. This was done with the help of the Zlib library [10]. For the demo, NAUV was commanded to submerge and execute a mission plan. The progression of the vehicle was monitored through Neptus with the help of status information received at the onshore control station (this was done through the WHOI Micro-modems). The operator would then select an arbitrary time to send an acoustic command for the NAUV to switch execution to another mission plan. That second plan consisted of a station keeping maneuver to be done at the surface. Upon reception of the switch command the NAUV interrupted the execution of the initial plan and headed to the station keeping position.

C. Follow vehicle over acoustic modem

The same TDMA specifications mentioned in the previous section were also used for this scenario. Figure 3 depicts a partial screenshot of the follow vehicle maneuver being executed and monitored using Neptus. Figure 4 presents data from the experiment. The blue crosses are positions where Swordfish was when it received messages containing NAUV's position. The first four blue crosses are quite close to each other. This is because the NAUV was still at the surface, enabling fast communications over the WiFi link. The messages were received less frequently when the NAUV was underwater.

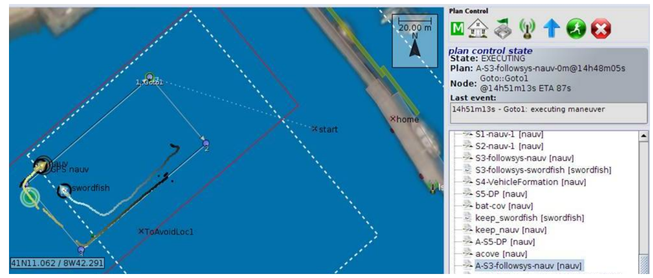

Fig. 3. Follow vehicle maneuver being supervised using Neptus Command and Control Unit.

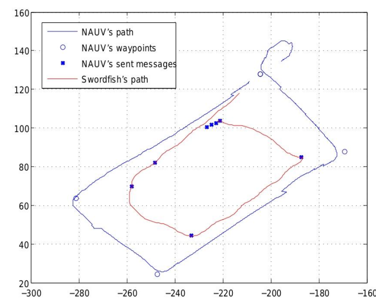

Fig. 4. Plot of the paths described by each vehicle.

D. Formation control over acoustic modem

In this section we will only present results for the formation controller using a Sliding Mode Control law. The base path to be tracked by the participating vehicles was designed in Neptus and is depicted in figure 5, in yellow color. The paths for each vehicle is then generated by adding an offset left and right of the base path. In figure 6 we present results obtained during the formation maneuver demo. The left plot depicts in blue and red the paths described by Swordfish and NAUV, respectively. The black colored path is the base path used to generate the remaining two. The circles are the waypoints that define the path. A red cross represents the position where Swordfish was when it received a message from NAUV. The same reasoning should be applied to the blue crosses. In order to maintain the formation pattern, the vehicles had to speed up and down. The plot on the right side of figure 6 depicts the speeds in meters per second of each vehicle during the execution of the plan. The red and blue crosses represent, respectively, the positions where Swordfish and NAUV were when they broadcasted their positions. Few messages were able to reach their destination (a total of 10 for the whole run), as the acoustic channel, at that specific time and place, did not allow for better performance.

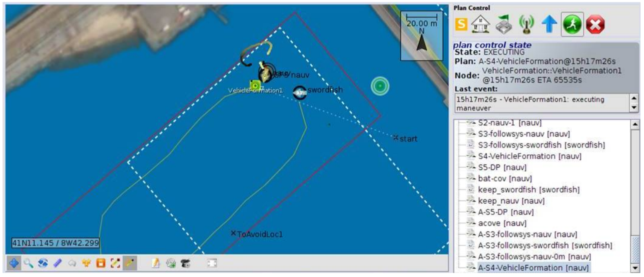

Fig. 5. Base path has it was designed in Neptus.

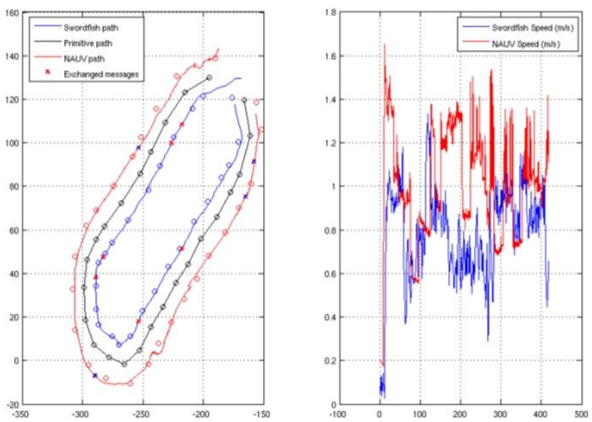

Fig. 6. Paths described by each vehicle during formation maneuver.

E. *Dynamic programming based feedback control*

The controllers were implemented in C++ and integrated, as a maneuver, in the AUV control software, DUNE. During the development phase, the control software was also tested in the simulation environment described in [11]. This simulation environment consists of replacing the sensor and actuator drivers by a simulation task offering the exact same software interfaces. The CPU time consumed by the simulation task is sufficiently low so that the whole application can be tested on the target CPU while standing on the bench. This allows us to detect potential problems in the implementation of the control system before deploying the vehicles on water. Figure 8 shows the results during the demonstration of this controller with the NAUV. The mission plan is depicted on figure 7.

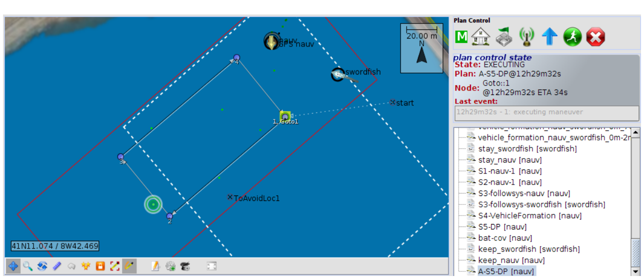

Fig. 7. Mission specification in Neptus.

The operation consisted of following a rectangular path. The control system was configured to switch to a new

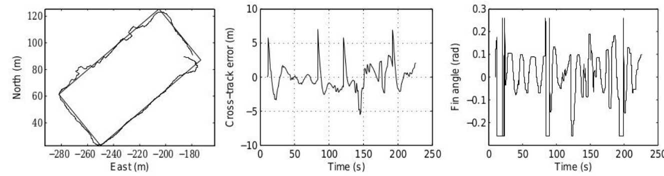

Fig. 8. Controller performance.

segment of the path as soon as the vehicle was at a distance of 5 meters from the current segments endpoint (the vertices of the rectangle, in this case). We remark that most of the disturbances observed in the trajectories of the first and second plots in figure 8 are mainly due to navigation errors introduced by the noisy updates of the acoustic system. Nevertheless, it can be observed that the results are similar to those obtained in simulation. The cross-track error only exceeds the expected maximum (6 meters, as defined above) in some of the sharp turns corresponding to the changes of segment. The actuation signal was also relatively smooth, except at the sharp turns. This is not surprising since the controller was not designed to handle such sharp turns. On those instants, the controller switched to the MTTR (minimal time to reach) control law which, as expected, produces a more aggressive actuation.

V. Conclusion and Future Work

This demonstration provided a glance at future operations of heterogeneous vehicle systems over inter-operated networks.

The deployment of the Manta gateways demonstrated underwater and WiFi communications coverage over the same geographic region, thus allowing operations where AUVs surface periodically to send data files to a remote station (e.g., the main ship) and to receive plan updates. The combination of wireless and underwater communications allows interleaving of signals (low-bandwidth) and communications (high-bandwidth) for maximum operational effectiveness and near real-time reaction. The operation of the vehicles in a mixed-initiative fashion enabled additional control of communications and added situational awareness. The systems approach enabled us to demonstrate multi-vehicle behavior with the help of coordinated plans and primitive maneuvers allowing interactions with other vehicles. DP-based feedback control proved to be robust and showed great promise to encoded complex control specifications which cannot be handled by other control techniques in an uniform manner.

In the future we would like to increase the data transmission rate in our acoustic networks. This will make operations with larger formations of vehicles a possibility and will improve the performance of formation keeping. It will also increase the amount of information that can be sent acoustically to the vehicle, thereby expanding the possibilities from a high level supervision perspective as well as in mixed initiative. For instance, instead of just triggering the start of a plan from the database through the acoustic channel, we could also send actual waypoints for the vehicle to track.

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